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FIBER OPTICAL ATTENUATOR

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FIBER OPTICAL ATTENUATOR

FIELD OF THE INVENTION

The present invention relates to the field of optical attenuators, and especially electronically variable attenuators suitable for use in fiber optical applications.

BACKGROUND OF THE INVENTION

Variable attenuators are important components in fiber optical test and measurement instrumentation and in fiber optical communication systems. The requirements of optical attenuators for use in such systems are that they should vary the intensity of the light transmitted without appreciably altering the spatial, temporal, spectral or polarization distribution of the light beam, and that they should be polarization insensitive.

Many types of variable attenuators have been described in the prior art. Mechanically variable attenuators, such as those using moveable or rotatable graded neutral density filters, or movable absorbing sections inserted into the optical path are bulky, complex and slow, and so are unsuitable for fast response optical communication use.

Electronically controlled fiber optical variable attenuators have been described in a number of prior art patents. In U.S. Patent No. 6,055,104 there is described a variable attenuator which uses a polarizing beam splitter and a polarization rotator, which could be a Faraday rotator, a magneto-optical effect crystal, or a liquid crystal. Variable attenuators using similar schemes of polarization rotation and control elements are described in U.S. Patent Nos. 5,999,305, 5,978,135, 5,973,821, 5,963,291, 5,867,300 and 5,727,109, and in the numerous previous references cited in these Patent documents.

All of these variable attenuators are generally complex in construction, in that they usually involve at least three optical elements, a polarizing element, an

electro-optical polarization control element and an analyzing element. Furthermore, since these attenuators depend for their operation on manipulation of the polarization of the wave being attenuated, care must be taken in their design and construction to ensure that they do not alter the polarization characteristics of the optical signal, thereby affecting the possible dispersion of the signal in its onward transmission, and even more important, that their attenuation properties are not affected by the polarization characteristics of the signal being attenuated.

There thus exists an important need for a simple, electronically controllable variable attenuator, which performs its function independently of the polarization of the optical signal on which it is operating.

The disclosures of each of the publications mentioned in this section and in the other sections of the specification, are hereby incorporated by reference, each in its entirety.

SUMMARY OF THE INVENTION

The present invention seeks to provide a new variable fiber optical attenuator which is compact, polarization insensitive, wavelength independent, simple in construction and operation, and of low manufacturing costs. The attenuator utilizes the cut-off phenomenon for single mode propagation of an optical wave down a single mode fiber. It is known that the dimensions of a single mode fiber are such that it can only support the lowest order mode of propagation, which is generally the fundamental mode, ideally having a Gaussian cross section. A wave with a higher order mode cannot propagate down the small dimension of the single mode fiber, and thus suffers strong attenuation.

There is thus provided in accordance with a preferred embodiment of the present invention, a variable attenuator consisting of an element capable of changing the phase of part of the cross section of an optical wave. Such a spatial phase change is equivalent to a change in the mode structure of the propagating

wave. The aforementioned element is preferably disposed between the ends of two closely positioned single-mode fibers, such that any optical wavefront coupling from one fiber to the other has to traverse the element. So long as the element is not activated, the lowest mode of propagation is unaffected, and the attenuator transfers the signal unattenuated from the input fiber to the output fiber. If the element is activated such that the phase distribution in the wave passing through is changed, the signal will be attenuated in accordance with the extent to which higher order modes are mixed into the low order mode originally present. When the mode is completely transformed to higher order modes, the wave is effectively completely blocked from entering the output single-mode fiber, and the attenuation is high. The level of attenuation is determined by the fraction of the wave which is converted to modes other than the lowest order mode. The light entering the output fiber in the higher order modes, which cannot propagate freely, leaks into the cladding of the fiber and gets scattered or absorbed by the fiber outer jacket.

A preferred element for performing the mode change is a liquid crystal element, whose cross section is preferably divided into pixels such that each pixelated part can be switched separately. The choice of pixel pattern in the liquid crystal element determines the spatial pattern of phase change impressed upon the traversing wave, and hence the higher order mode transmitted by the element. The fraction of the mode-transformed optical power transmitted by the attenuator is dependent on the degree of phase change imparted by the switched pixels. When the phase change is slight, only a small fraction of the incident wave is transformed into the selected higher order mode. When the phase change is π, all of the incident wave is transformed into the selected higher order mode, and the attenuation is maximum. The voltage impressed across the liquid crystal element thus controls the attenuation of the device. It is to be understood that although a liquid crystal element is a convenient, low cost and widely available element, the phase changing element can be of any suitable type, such as one based on the Faraday effect, the magneto-optical effect, the electro-optical effect, or any other

suitable opto-electrical effect.

The attenuator according to the preferred embodiment of the present invention described above, is simpler than many of the prior art attenuators mentioned hereinabove, since it has only one operative optical element, the phase changing element, and it does not require any polarization optics or any other expensive components to reject the unwanted light.

Optical transmission down fibers results in the mixing of the polarizations of the transmitted signals, because of the constant reflections from the fiber walls. A very important aspect of attenuator operation is therefore that it be polarization insensitive, since the polarization of the input signal is generally unknown and mixed. Since the attenuator according to the present invention is not directly dependent for its operation on the polarization properties of the transmitted light, the attenuator, if correctly designed, can thus be made essentially polarization independent. In order to be so, the attenuator has to act uniformly on all polarization states. However, the operation of a liquid crystal device usually depends on the polarization of the input light. For example, an electric field applied to a parallel nematic liquid crystal cell affects only the phase of the linear component of the polarization which is parallel to the alignment layers on the cell boundaries. For this reason, if a liquid crystal, for example, is used as the phase shifting element in the attenuator of the present invention, the element must be so selected and arranged that any inherent polarization effects are preferably self-canceling or self-compensating.

In the attenuator of the present invention, polarization insensitivity is ensured by one of several preferred methods. The first method is by optimizing the phase changing element or elements such that both orthogonal phase components of the incident wave undergo the same phase change. This can preferably be achieved either by the use of two identical phase-changing elements in series, each providing complementary phase changes for the two orthogonal polarization components of the input signal, or by the use of a 180° twisted nematic element, which then has the same total phase change for the two

orthogonal polarization components of the signal. Another preferred method is the use of a liquid crystal element with separate pixels having orthogonal aligning layers, and having at least a 2-fold symmetry, such that any change in phase arising from one part of the element on one of the orthogonal components of the input signal, is compensated by the same change in phase on the other orthogonal component arising from a symmetrically opposite part of the element. As a consequence, regardless of the polarization direction of the light incident on it, the phase changing element will affect the relative phase distribution across the wavefront in the same way, thus resulting in polarization insensitive operation.

The variable optical attenuator described above operates in a guided wave mode. According to other preferred embodiments of the present invention, it can also be constructed to operate in a free space mode.

Furthermore, the variable optical attenuator described above operates in a transmission mode. According to other preferred embodiments of the present invention, it can also be constructed to operate in a reflection mode.

Furthermore, the variable optical attenuator described above is constructed of discrete components. According to other preferred embodiments of the present invention, the variable optical attenuator can also be constructed by means of integrated optics techniques on a single semiconductor substrate, such a silicon, with the detector, the liquid crystal device drive circuits and the control electronics all integrated into one chip, and the liquid crystal device itself intimately mounted on the chip.

Furthermore, the variable optical attenuator described above is constructed with the cross section of the phase changing element divided into pixels such that each pixelated part can be controlled or switched separately. It is to be understood that the use of the term pixels throughout this application, and as claimed, is not meant to be limited to pixels defined by discrete pixelated electrodes on the surface of the element, as conventionally understood by the term, but can preferably refer to any method of ensuring that part or parts of the element are controlled or switched differently from other parts. These parts are thus termed

"pixels". Such pixels can be defined, in one preferred example, by electric fields induced into the element by electrodes remotely located from the pixels to be switched, or not immediately above the pixels to be switched.

Furthermore, the optical attenuators described above are variable optical attenuators. According to other preferred embodiments of the present invention, the attenuator can be a fixed attenuator with a predetermined attenuation value according to the fixed phase element used in the device.

Furthermore, according to other preferred embodiments of the present invention, an array of variable optical attenuators of the type described hereinabove, can be utilized to construct a novel fiber optical gain equalizer.

In accordance with yet another preferred embodiment of the present invention, there is provided variable optical attenuator consisting of an input fiber for receiving an input optical signal to be attenuated, an output fiber for outputting the attenuated optical signal, at least one phase changing element disposed in the optical path between the input fiber and the output fiber, and a drive source operative to change the phase of light passing through at least part of the at least one element.

In the variable optical attenuator described above, the change in the phase of light passing through the at least part of the at least one element may be operative to change the mode structure of at least part of the input optical signal such that that part of the input optical signal cannot propagate freely in the output fiber.

In accordance with still another preferred embodiment of the present invention, in the variable optical attenuator described above, the input optical signal may have an effectively fundamental mode structure and the output fiber may be a single mode fiber, such that the mode structure of at least part of the input optical signal is changed to a higher order mode, and as a result, that part of the input signal cannot propagate freely through the output fiber.

There is further provided in accordance with yet other preferred embodiments of the present invention, variable optical attenuators as described

above, and wherein the at least one phase changing element is a liquid crystal element. The at least one phase changing element may preferably consist either of a serial pair of parallel aligned liquid crystals, orthogonally aligned such that the attenuator is insensitive to the direction of polarization of the optical signal, or a serial pair of 90° twist liquid crystals, aligned in parallel such that the attenuator is insensitive to the direction of polarization of the optical signal, or a liquid crystal divided into at least two orthogonally aligned pixels, such that the attenuator is insensitive to the direction of polarization of the optical signal.

In accordance with still more preferred embodiments of the present invention, there are provided variable optical attenuators as described above, and wherein the phase changing element is either an electro-optic element, or a Faraday effect element or a magneto-optical element.

Furthermore, the part of the element may preferably be defined by at least one pixel on the element, or by two pixels, or by four pixels. In the later case, the drive source is operative to change the phase of light passing through two diagonally opposite ones of the four pixels.

There is further provided in accordance with still other preferred embodiments of the present invention, variable optical attenuators as described above, and wherein the input fiber and the output fiber are disposed such that light passes by transmission between them, or wherein the attenuator also includes a reflecting surface and the input fiber and the output fiber are disposed such that light passes by reflection between them. The reflecting surface may preferably be formed on the rear side of the phase changing element.

Furthermore, in the variable optical attenuators described above, the at least one pixel may be formed by means of at least one pixelated electrode located essentially over the at least one pixel, or by means of at least one electrode located remotely from the at least one pixel.

In accordance with a further preferred embodiment of the present invention, there is also provided an optical attenuator consisting of an input fiber, an output fiber and at least one phase changing element operative to change the

phase of part of the cross section of light passing from the input fiber to the output fiber.

In addition, the change in the phase of part of the cross section of light passing from the input fiber to the output fiber may preferably be such that the mode structure of the light is changed such that the light cannot propagate freely in the output fiber.

Furthermore, the input fiber may preferably be a single mode fiber, and the output fiber a single mode fiber, and the mode structure of at least part of the light thus changed to a higher order mode, such that the part of the light cannot propagate freely in the output fiber.

There is provided in accordance with yet a further preferred embodiment of the present invention, an optical attenuator as described above, and wherein the at least one phase changing element is a liquid crystal element.

Furthermore, the at least one phase changing element may preferably consist either of a serial pair of parallel aligned liquid crystals, orthogonally aligned such that the attenuator is insensitive to the direction of polarization of the light, or a serial pair of 90° twist liquid crystals, aligned in parallel such that the attenuator is insensitive to the direction of polarization of the light, or a liquid crystal divided into at least two orthogonally aligned pixels, such that the attenuator is insensitive to the direction of polarization of the light.

In addition, according to other preferred embodiments of the present invention, the at least one phase changing element may be pixelated.

There is even further provided in accordance with a preferred embodiment of the present invention, an optical attenuator as described above, and wherein the change in the phase of part of the cross section of light is effected by means of electrodes associated with the at least one phase changing element. The attenuator may then preferably be a variable attenuator.

Furthermore, in accordance with yet another preferred embodiment of the present invention, there is provided an optical attenuator as described above, and wherein the input fiber and the output fiber are disposed such that light passes by

Fig.1 is a schematic illustration of a variable fiber optical attenuator, constructed and operative according to a preferred embodiment of the present invention;

Fig. 2 is a view in the direction of the light propagation, of the cross-section of a pixelated liquid crystal element, for use in the variable optical attenuator shown in Fig. 1;

Fig. 3 shows an alternative pixel arrangement to that shown in Fig. 2, in which the liquid crystal is divided into four pixels;

Fig. 4 is a schematic side view of a liquid crystal element, according to a further preferred embodiment of the present invention, in which the electrodes for applying the electric field for controlling the liquid crystal are located at the side of the crystal;

Figs. 5A to 5C illustrate several different geometrical methods from that shown in Fig. 1, of arranging phase changing elements to spatially change the phase over the input beam;

Fig. 6 is a schematic illustration of another preferred embodiment of an optical attenuator according to the present invention, similar to that shown in Fig. 1, but executed in free space;

Fig. 7 is a schematic illustration of another preferred embodiment of the present invention, similar to that shown in Fig. 6, but using a GRIN lens rod for producing a collimated beam of light instead of the free space embodiment with a conventional lens shown in Fig. 6;

Fig. 8 is a schematic illustration of a variable optical attenuator according to another preferred embodiment of the present invention, using a dual fiber collimator in a reflective embodiment;

Fig. 9 is a schematic illustration of another preferred embodiment of the present invention, similar to that shown in Fig. 8, but executed in free space from the ends of the input and output fibers instead of using a dual fiber collimator;

Fig. 10 is a schematic illustration of a fixed fiber optical attenuator, constructed and operative according to another preferred embodiment of the

present invention;

Figs. 11A and 11B are schematic illustrations of two alternative preferred embodiments of an integrated phase changing element, for use in a variable optical attenuation control element, according to the present invention;

Fig. 12 is a schematic illustration of a multichannel gain equalizer utilizing an array of variable optical attenuators, constructed and operative according to a preferred embodiment of the present invention;

Fig. 13 is a schematic illustration of a multichannel gain equalizer constructed and operative according to another preferred embodiment of the present invention, utilizing an array of reflective variable optical attenuators; and

Figs. 14A to 14C show a number of preferred configurations of phase changing liquid crystal elements, which provide attenuators of the present invention with polarization insensitive operation.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Reference is now made to Fig. 1, which illustrates schematically a variable fiber optical attenuator, constructed and operative according to a preferred embodiment of the present invention. The attenuator consists of two sections of single-mode optical fiber 10, 12, between whose ends is disposed a liquid crystal element 14, such that light passing from the end of one of the fibers to the other must traverse the liquid crystal film. The liquid crystal element 14 preferably has transparent electrodes 16, 18 deposited on its faces, such that switching can be simply accomplished by application of a variable voltage 20 across the electrodes. The electrodes are pixelized (not visible in this side view, but shown in Figs. 2 and 3 below), so that preselected sections of the liquid crystal element can be switched separately. The fiber end sections and the liquid crystal element are rigidly held in contact, preferably by means of an external sleeve 22, and a sealant material 24 inside the sleeve supports the components in a stress-free and hermetic manner. When no voltage is applied to the electrodes, the whole of the

liquid crystal is optically uniform and induces no phase shift into the light traversing it. All of the input optical power in fiber 10 passes into the output fiber 12 without any phase change, and consequently, is able to propagate through the output fiber virtually without insertion loss.

The operation of the attenuator of Fig. 1 can be elucidated by reference to Fig. 2, which is a view in the direction of the light propagation, of the cross-section 30 of a preferred liquid crystal element, for use in such a variable optical attenuator. Each of the electrodes on the surfaces of the element has two pixels, dividing the element into two halves. The control voltage is preferably applied to one of the pixels 32, and at its maximum rated value, modifies the liquid crystal under that pixel, such that the light passing through the pixel is phase shifted by π. The liquid crystal under the other pixel 34 is unchanged. The whole of the light passing through the liquid crystal element is therefore transformed to an anti-symmetric field distribution, which cannot couple to the symmetric fundamental lowest order mode of the fiber. All the light is converted to the HE_{12} and higher order asymmetric modes, which cannot propagate in the fiber. The attenuator is then at its maximum value, ideally fully blocking the light passage. For intermediate values of applied voltage, when the phase shift for the light passing through pixel 32 is less than π, only part of the light is transformed to the anti-symmetric, higher order mode, and the light is thus partially attenuated. The level of light transmitted is thus a function of the applied voltage. It is to be understood that though the electrode structure of Fig. 2 has been described in terms of two separate electrodes on each surface, each covering a pixel of half of the surface, in practice, alternatively and preferably, there is need for a phase control electrode on one half of the element only in order to generate the higher order antisymmetric mode.

Reference is now made to Fig. 3, which shows another preferred pixel arrangement, for preferred use in the present invention. In this embodiment, the liquid crystal is divided into four pixels, with the control voltage applied to two diagonally opposite pixels 40, 42. For clarity, the drive voltages are shown in Fig.

3 as coming from separate sources, though it is to be understood that they will generally come from one source. As a result of this four-fold symmetry, the modes transmitted through the element are converted to even higher order modes, which are more strongly attenuated by the single mode fiber than the HE_{12} mode.

Although the invention has been described only in terms of the pixel configurations shown in Figs. 2 and 3, which result in the production of the two above-mentioned mode patterns respectively, it is to be understood that the invention is equally operative when the liquid crystal element produces other mode structures which cannot be propagated by the single mode fiber at the output to the attenuator.

The embodiments shown in Figs. 2 and 3 have been described using transparent pixelated electrodes located above the pixelated areas of the liquid crystal device where it is desired to change the phase. Reference is now made to Fig. 4, which shows a further preferred embodiment of the present invention, in which the pixelated areas are defined by means of electrodes located remotely from those areas themselves. Fig. 4 is a schematic side view of a liquid crystal element 43, according to a further preferred embodiment of the present invention, in which the electrodes 44 for applying the electric field for controlling the liquid crystal are located at the side of the crystal. The electrode pattern and the control voltages applied to them are arranged to be such that a field gradient is set up across the element, which defines pixel areas where the phase is changed, and other pixel areas where it is not. Since the electrodes do not cover the central area of the element, through which the optical signal passes, they do not have to be transparent.

Furthermore, although the pixel structure and their drive voltages are shown in Figs. 2 and 3, and in the following figures, in a schematic form, it is understood that known microelectronic methods and techniques could be used to pixelize the liquid crystal and provide the drive voltage circuits.

Furthermore, although the above preferred embodiments have been described using a liquid crystal element as the phase changing element, and drive

voltages as the control parameter acting thereon, it is to be understood that the invention can also be executed using other types of phase changing elements, and other forms of drive control, such as current drives, as appropriate.

Furthermore, although the above preferred embodiments have been described using a single liquid crystal element controlling the phase change over the whole of the traversing optical beam, it is possible to spatially change the phase over the beam in any other suitable geometric arrangement of elements. Some of these arrangements are shown in Figs. 5A to 5C.

Fig. 5A is a schematic view of a series pair of phase changing elements 45, 46, wherein each phase changer controls the phase of part of the beam passing through it. The pixel geometry and drive arrangements may become accordingly simpler in such an embodiment.

Fig. 5B is a further preferred embodiment, wherein the two elements 47, 48, are offset, such that each of the different spatial parts of the beam whose phase is to be controlled, passes through its own phase control element.

Fig. 5C is even a further preferred embodiment, wherein only one phase changing element 49 is used, but unlike the embodiments of Figs. 2 and 3, this element is disposed such that only part of the beam passes through it. That part is then phase changed by the single element 49, thus generating the higher order mode required for the operation of the attenuator.

In explaining the operation of the attenuators of the above-described embodiments of the present invention, although reference is sometimes made to input and output fibers, it is to be understood that except where specifically stated to the contrary, the attenuators are non-directional devices, and operate equally well with the light signal incident from either end, both hereinabove and in the descriptions of successive embodiments.

The attenuation values attained for any given control voltage can be stabilized by the use of known temperature control techniques for the component, thereby improving stability and performance. Preferred methods for doing so include use of a heating element which keeps the component stabilized at a

temperature above the ambient, or by means of a Peltier heating/cooling element.

Reference is now made to Fig. 6, which is a schematic illustration of another preferred embodiment of the present invention, similar to that shown in Fig. 1, but executed in free space instead of in a waveguide-like structure. The attenuator consists, like Fig. 1, of two sections of single-mode optical fiber, an input section 10, and an output section 12. The signal emerging from the end of the input fiber 10 diverges in free space and is collimated by the lens 50. The signal then traverses the phase changing element 52, and is focused by a second lens 54 onto the end of the output fiber 12. As in the previously described embodiments, the phase changing element 52 is controlled by a variable applied voltage 56 to change the mode pattern of the wave traversing the element. The phase changing element 52 is preferably a pixelized liquid crystal device.

Reference is now made to Fig. 7, which is a schematic illustration of another preferred embodiment of the present invention, similar to that shown in Fig. 6, but using a GRIN lens rod 55 for producing a collimated beam of light instead of the free space embodiment with a conventional lens, as shown in Fig. 6. A second GRIN lens rod 56 is then preferably used for focussing the phase-amended beam into the output fiber 12. This embodiment has an advantage that it can be constructed much more compactly and in a more integrated manner than that of Fig. 6.

Reference is now made to Fig. 8, which is a schematic illustration of a variable optical attenuator, constructed and operative according to another preferred embodiment of the present invention. This embodiment is a reflective embodiment, which uses a dual fiber collimator 60 as the input/output device. The signal to be attenuated is input by the fiber 62, and is converted by the dual fiber collimator 60 into a collimated output beam 64. This output beam traverses the electrically variable phase changing element 66, which is preferably a pixelized liquid crystal element, and is reflected at the rear side of this element 66, either by means of a reflective coating 68 on the rear surface, or by means of a separate mirror element behind the phase changing element. The spatially

phase-amended, reflected beam re-enters the dual fiber collimator 60, and the level of the signal which can be recoupled from the output fiber 69, is dependent on the fraction of the input light which has been transformed into higher order asymmetric modes. In this way, the attenuation level can be varied by the applied voltage on the variable phase change device 66.

Reference is now made to Fig. 9, which is a schematic illustration of another preferred embodiment of the present invention, similar to that shown in Fig. 8, but executed in free space instead of using a dual fiber collimator. The input and output signals to and from the attenuator are via the ends of two single mode fibers, 80, 82, aligned at an angle to each other, and positioned closely in front of a reflective variable phase changing element 84, similar to that shown in Fig. 8. The reflective phase changing element, preferably a pixelated liquid crystal device, is aligned with its normal at the bisecting angle between the two fiber ends, such that light emitted from the input fiber passes through the phase element 84, has its mode structure changed according to the setting of the phase changing element, and is reflected back into the output fiber 82, wherein the level propagated depends on the extent of higher order asymmetric modes in the output light.

Reference is now made to Fig. 10, which is a schematic illustration of a fixed fiber optical attenuator, constructed and operative according to another preferred embodiment of the present invention. This embodiment is similar to that shown in Fig. 1, except that the phase-changing element 86 is fixed, and the support sleeve 88 does not need to convey any electrical control signals, as in Fig. 1. The attenuation value is predetermined according to the fixed phase-changing element used in the device. This embodiment is therefore particularly simple in construction.

Furthermore, according to other preferred embodiments of the present invention, the conversion of the transmitted light into higher order asymmetric modes can also be achieved by the insertion of an asymmetric attenuating film into the beam path, instead of the use of an asymmetric phase shifting element.

Though the use of attenuating films is known in prior art attenuators, to the best of the inventor's knowledge, such films are used to attenuate the transmitted signal directly by absorption. According to this embodiment of the present invention, a comparatively low attenuation, asymmetric film can degrade the symmetry of the beam, so that the fundamental mode of propagation is depressed, and the transmission through the single-mode output fiber is attenuated far in excess of the effect of the direct attenuation in power resulting from the attenuating film in the optical path.

Reference is now made to Fig. 11A, which is a schematic illustration of an integrated reflective phase changing element, for use in a variable optical attenuator, according to another preferred embodiment of the present invention. The integrated element can be used in any of the above shown reflective attenuator embodiments, such as those shown in Figs. 8 and 9. The element differs from those described hereinabove, in that it preferably incorporates a photodetector element and electronic circuitry, such that the element can be used as an integrated feedback controller for maintaining the attenuation at a predefined level. The element is preferably constructed on a substrate of silicon 90, on which all of the opto-electronic elements and circuits are integrated. The substrate is preferably mounted on an integrated circuit header 91, with socket pins 92 for making input and output and power supply connections. Alternatively and preferably, the substrate can be integrated into a complete opto-electronic circuit, including connection to both input and output fibers.

A phase changing element 94, such as a liquid crystal device, is preferably incorporated into the device at the front of the substrate, and is protected by means of a thin glass cover plate 93, which also preferably incorporates transparent switching electrodes, defining the pixels of the element. The liquid crystal material is thus sandwiched between the glass front cover plate 93, and the front surface 98 of the silicon substrate. The drive circuits 95 for the electrodes are preferably integrated into the silicon substrate. The front surface 98 of the silicon substrate is optically polished to provide a reflective surface for the

attenuator. A small fraction of the light is preferably allowed to pass through a small pinhole of unpolished area in the surface of the silicon, into the silicon substrate. Alternatively and preferably, a small percentage of portion of the signal incident across the whole of the polished silicon front surface, passes through the surface, since the reflectivity of the surface is not 100% and thus allows part of the incident light to leak through. A photodetector element 96, integrated into the silicon substrate, detects this light signal, and its level is determined by detector amplifier circuitry 97, also preferably executed on the silicon substrate. The amplified electronic output signal from the detector circuit is used as a control signal equivalent to the level of optical power incident on the integrated reflective phase changing element. This arrangement is thus equivalent to the measurement of the incident light by means of a detector-terminated coupler on the input line.

The phase changing element itself is precalibrated such that the attenuation produced by the complete variable optical attenuator unit is a well-defined function of the voltage applied to the unit. Thus, application of a specific voltage leads to a corresponding attenuation of the input light signal. In order to ensure accurate correspondence between the applied voltage and the attenuation, it may be necessary to temperature stabilize the unit. In order to maintain a predefined output level from the unit, regardless of changes in the input signal level, the control signal from the back-leak is used as a feedback signal to compensate for any changes in input power level, while the voltage applied to the phase element determines the attenuation level. The output level is maintained constant by maintaining the product of these two control signals effectively constant. The unit can thus be used as a single-chip integrated variable optical attenuator, of compact dimensions, whose attenuation level can be preset by an input voltage signal, and whose attenuation or output level can be maintained at a constant level by means of electronic feedback. All of the functions are integrated on the single chip, thus keeping the production costs low. It is appreciated that although this embodiment has been described in terms of a silicon component, it could just as readily be implemented on any other preferred opto-electronic

substrate, such as gallium arsenide, germanium, indium phosphide, or any other suitable semiconductor material.

In the embodiment shown in Fig. 11A, the actual output power from the attenuator is not measured, either directly or indirectly. The long term accuracy and stability of the attenuator is dependent on the accuracy and stability of the phase-changer calibration. A method of using the attenuated output power as the control for the attenuation level provided would be a more direct and accurate method of operation of this embodiment. Consequently, as an alternative to the detection of the incident power by means of a back-leak in the silicon reflecting surface, Fig. 11B schematically shows how the attenuation change can be detected by means of the level of the light which leaks into the cladding from that entering the output fiber. The level of light leaking in this manner is proportional to the level of light not coupled into the output fiber because its mode has been degraded by means of the phase shift imparted by the phase shifting element, and is thus proportional to the attenuation level of the device. In Fig. 11B, the reflected phase-shifted light having a higher order asymmetric mode of propagation, and therefore incapable of being propagated back down the connection fiber 64, is shown being deflected to the sides 88, where it is detected by one or more detector units 99 positioned at the side of the fiber. This signal is dependent on the attenuated output signal of the attenuator, and is input to the relevant integrated silicon amplifier circuits, where it is compared with an externally provided reference level signal corresponding to the attenuation level desired, and also input to the silicon circuit. The resulting difference signal is amplified to generate a variable voltage which is used to adjust the phase change induced into the relevant spatial sections of the liquid crystal phase changing element 94, thus maintaining a constant and stable output level.

Reference is now made to Fig. 12, which is a schematic illustration of a multichannel gain equalizer 100, utilizing an array of variable optical attenuators, constructed and operative according to a preferred embodiment of the present invention.

The input optical signal, composed of a number of separate signals, each at its own characteristic wavelength, is input by means of the input fiber 102. The function of the gain equalizer 100 is to bring all of the separate signals to the same amplitude, in order to optimize system power budget. The input signal is input into a demultiplexer 104, which separates the individual wavelength components of the signal into n separate channels, λ_1, λ_2, λ_3, ...λ_n, one for each wavelength range. Such a demultiplexer can preferably be constructed of a dispersive grating. Each of these channels is input into its own variable optical attenuator 106, VOA_1, VOA_2, VOA_3, ... VOA_n, according to preferred embodiments of the present invention. The levels of the signals in each channel 1, 2, 3, ...n, are detected, preferably by means of in-line signal detector elements, 108, and a feedback signal from each detector element is used to control the level of attenuation of each VOA. The resulting signals from all of the separate channels are thus brought to the same level, and are recombined in the multiplexer unit 110, into a multi-channel, gain-equalized, output signal for outputting through the output fiber 112.

In order to enable the gain equalizer to operate bidirectionally, each of the "input" channels can optionally be provided with its own in-line signal detector elements 109, such that when the unit is used in the reverse direction, or when the input comes from the reverse direction, these detector elements 109 are operative to detect the attenuated output power level, instead of the detector elements 108 on the other side of the VOA's. Means should preferably be provided to determine in which direction the signal is travelling, since the equalizer must be controlled by the light signal detected after attenuation. The direction of use can either be predetermined by the system configuration, or can be determined on-line during use by comparing the signal levels detected by detector elements 108 and 109.

The gain equalizer preferably utilizes an array of integrated variable optical attenuators as this enables the construction of a particularly compact gain equalizer. Alternatively and prefer, it can be constructed of separate variable

optical attenuators of the type shown in the previous figures, in a free-space embodiment. Such embodiments include both transmissive embodiments of variable optical attenuators, as illustrated in Fig. 12, and reflective types.

According to further preferred embodiments of the present invention, detector elements such as those labeled 108 and 109 in Fig. 12, can be installed anywhere in the optical channel where the power level is to be monitored. The signal monitoring can even be performed remotely from the gain equalizer, such as at the receiver station or at an en-route repeater unit, either of which could be at a considerable distance from the gain equalizer itself. In this way, the gain equalization is performed on the basis of the signal strengths of each channel detected at the destination point of the signal, where the gain equalization is important for the system power budget.

Reference is now made to Fig. 13, which is a schematic illustration of a multichannel gain equalizer, constructed and operative according to another preferred embodiment of the present invention, utilizing a free space array of reflective variable optical attenuators. Like the reflective embodiment shown in Fig. 8, a dual fiber collimator 60 is preferably used as the input/output device. The signal to be attenuated is input by the fiber 62, and is preferably converted by the dual fiber collimator 60 into an approximately collimated output beam 64. A dispersive grating 114, operates as a demultiplexer, separating the input signal beam 64 into separate wavelength channels λ_1, λ_2, λ_3, ..., each of which falls onto a different spatial location 115, 116, 117, on the reflective phase-changing element 113. Each spatial location is associated with a separate pixel of the phase-changing element, such that each wavelength channel can be individually controlled by separate pixels. The reflected, phase-modulated channels are multiplexed by the same grating 114 as was operative as the demultiplexer, and are input to the dual fiber collimator 60, from which the recombined gain equalized signal is output on fiber 69.

In the free-space schematic embodiment illustrated in Fig. 13, no signal strength detectors are shown, and the individual channel signal levels may

preferably be determined at a remote site. Alternatively and preferably, the reflective pixelated phase-changing element 113 may be of an integrated type containing an array of detectors, such as those illustrated in Figs. 11A or 11B, and the individual channel signal strengths adjusted on-line. This embodiment thus enables a compact and cost-effective gain-equalizing unit.

In the optical embodiment shown in Fig. 13, an approximately collimated beam is shown at the output of the dual-fiber collimator 60. It is to be understood that this embodiment is only one possible configuration of this aspect of the invention. The reflective multichannel gain equalizer can be equally well constructed using alternative optical set-ups, such as with a dual fiber collimating coupler outputting a point source, and a beam expander to diverge the output beam, or with any other suitable combination of optical elements for beam forming and focusing purposes. Likewise, a lens can preferably be used at the output of the dual fiber collimator 60 to ensure that the collimated beam 64 properly fills the aperture of the dispersive grating 114. Furthermore, in the embodiment shown in Fig. 13, a concave grating 114 is used as the dispersive element, such that the light from each channel is focussed by the grating itself onto the reflective pixelated phase-changing element. According to another preferred configuration of this embodiment, a plane grating can be used, with a positive lens operative to focus the channels onto their correct location on the phase-changing element.

Since attenuators according to the present invention, unlike many of the prior art attenuators, are not directly dependent for their operation on manipulation of the polarization properties of the transmitted light, the above preferred embodiments have been described in terms of their operating structure as an attenuator, without consideration of the ancillary requirements of the conditions to ensure polarization independence. These requirements have been mentioned in the summary section, and are particularly relevant to embodiments which use liquid crystals as the phase changing elements, as the operation of a liquid crystal is generally dependent on the polarization of the incident light.

Reference is now made to Figs. 14A to 14C, which show a number of preferred configurations of phase changing liquid crystal elements, which provide attenuators of the present invention with polarization insensitive operation.

In Fig. 14A, there is shown a preferred representation of a pair of identical parallel nematic liquid crystals, X and Y, for use together in series as a single pixel of a phase changing element in any suitable embodiment of the optical attenuators shown hereinabove. The two crystals are identical, but are mutually rotated at 90° to each other such that the alignment layers of the nematic chains of the two elements are orthogonal. An identical electric field is applied to both elements, to effect the same phase change in both. It is to be understood that the pair of liquid crystal elements shown in Fig. 14A represents only one of the pixels of the complete phase-changing element of the present invention, and that the complete phase-changing element consists of at least two such pixels in order to effect a spatial phase change in the incident signal beam. The effect of the illustrated pair of elements on the polarization of the light passing therethrough is taken as an example of the effect on the polarization of the light passing through any of the pixels of the complete phase-changing element.

An incoming light signal of any polarization direction can be split into two orthogonal polarization components, denoted P_x and P_y, where x and y are respectively the alignment directions of the first and second liquid crystal elements. Referring now to Fig. 14A, P_x is shown pointing out of the page, and P_y is in the plane of the page and vertical. Each of the components is phase shifted in passage through the liquid crystal elements by an angle Φ given by the expression:

$$\Phi = nl \cdot 2\pi/\lambda$$

where n is the refractive index in the element for the polarization direction of the light, l is the length of the element, and λ is the wavelength of the light. The component P_x is parallel to the alignment direction of liquid crystal element X, and its phase is therefore shifted, in passage through the element, by an angle Φ equal to $n\ l \cdot 2\pi/\lambda$, where n is the refractive index in the element for parallel

polarized light. After passage through element X, the P_x component passes through element Y, whose alignment direction is orthogonal to the polarization direction of P_x, and its phase is therefore shifted by an angle $n_+ l \cdot 2\pi/\lambda$. The phase shift on component P_x in passing through both elements is thus $(n \; + n_+)l \cdot 2\pi/\lambda$.

Component P_y on the other hand, undergoes a phase shift of $n_+ l \cdot 2\pi/\lambda$ in passage through the first element X, and a phase shift of $n \; l \cdot 2\pi/\lambda$ in passage through element Y, resulting in a total phase shift of $(n \; + n_+)l \cdot 2\pi/\lambda$, identical to that undergone by component P_x. The net result is that both components undergo exactly the same phase change in passage through the two liquid crystal elements.

Since light having any incident polarization direction can be split up into two such orthogonal components relative to the element orientations, this combination of elements will always impart the same total phase shift to the input light, regardless of the incident polarization direction. Having undergone the same phase shift, the two components thus result in the same optical transmission loss through the attenuator, such that the attenuator is polarization independent. The actual value of phase shift imparted to the incident light is varied in the manner described above by applying an identical spatially pixelated electric fields to both of the elements.

Reference is now made to fig. 14B, which is a schematic representation of an element arrangement, according to another preferred embodiment of the present invention which ensures polarization insensitive operation of the variable optical attenuators described hereinabove. Like the embodiment shown in Fig. 14A, also in Fig. 14B, the effect of the polarization independence is illustrated for passage of the light signal through one pixel of the complete phase-changing element only. In this embodiment, two identical liquid crystal elements 118, 119, are again used, but this time, each has a 90° twist geometry, and they are identically aligned in series with each other. As in the embodiment of Fig. 14A, an incoming light signal of any polarization direction can be split into two orthogonal polarization components, which in this embodiment are denoted P_x and p_y, so that the different relative intensities of the two components can be

identified. In this embodiment, x and y are parallel respectively to the initial and final directions of alignment of the layers in the 90° twist elements. Each of the elements, besides imparting its characteristic phase change to the light according to the element geometry and any applied field, rotates the polarization direction of each of the components P_x and p_y by 90°. Thus, the component P_x after traversing element 118 emerges with its polarization orientation in direction y, and is denoted by P_y. Similarly, the component p_y after traversing element 118 emerges with its polarization orientation in direction x, and is denoted by p_x. Both of these vector components now enter the second element 119, which is identical to the first. In this second element, the component P_y undergoes a further 90° polarization rotation, and emerges as P_x, i.e. with the identical intensity and polarization direction as it initially had when incident on element 118. Similarly, the component p_x undergoes a further 90° polarization rotation, and emerges as p_y, i.e. it too has the same intensity and polarization direction as it initially had when incident on element 118. Thus the two output components when recombined recreate the input signal in intensity and polarization, but with a phase change imparted according to the element geometry, and according to any applied electric fields. Since light having any incident polarization direction can be split up into two orthogonal components relative to the element orientations, such as P_x and p_y, this combination of elements too will always impart the same total phase shift to the input light, regardless of the incident polarization direction.

Reference is now made to Fig. 14C, which schematically illustrates a further arrangement for ensuring that the phase changing liquid crystal elements renders the attenuator of any of the above mentioned embodiments insensitive to the polarization of the input light. Fig. 14C is a face view of a liquid crystal element 120 divided into two separate pixels whose alignment layers are orthogonal. In pixel 122, the layers are aligned in the x-direction, and in pixel 124, in the y-direction. As previously, an incoming light signal of any polarization direction can be split into two orthogonally polarization components,

denoted P_x and P_y. The effect of transmission of the incident light signal is now considered separately for the two differently oriented pixels.

Using the nomenclature of the description of the embodiment of Fig. 14A, in traversing pixel 120, whose alignment direction is parallel to the x-direction, the component of polarization P_x undergoes a phase shift proportional to n l. The component of polarization P_y undergoes a phase shift proportional to n_+l. In traversing pixel 122, whose alignment direction is parallel to the y-direction, on the other hand, the component of polarization P_x undergoes a phase shift proportional to n_+l, while the component of polarization P_y undergoes a phase shift proportional to n l. The output intensity of the P_x component, resulting from the addition of the light from the two pixels, is thus proportional to $(n \;\; + n_+)\, l$. The output intensity of the P_y component, resulting from the addition of the light from the two pixels, is also proportional to $(n \;\; + n_+)\, l$. The P_x and P_y components have both thus undergone identical phase shifts proportional to $(n \;\; + n_+)\, l$. The net result is that after combining the light after passage through both pixels, both components of the incident signal have undergone exactly the same overall phase change, and without dependence on the initial polarization direction of the incident signal, which determines the relative amplitude of the two components.

In operation, the application of an electric field across the liquid crystal then results in the rotation of the alignment direction in both pixels towards the direction of the field, and the adding of an additional phase change to the signal, according to the magnitude of the field applied. The attenuation is thus varied according to the applied electric field. It is not necessary, according to this preferred embodiment, for the electrodes to be pixelated. Their function in this embodiment is simply to apply a field across the whole of the element surface. The elements are preferably constructed such that the no-field phase change through them is a multiple of 2π, such that without the application of any field, the attenuation is at its nominally zero value.

It is understood that the polarization compensation effect described above in the two pixel embodiment of Fig. 14C, is operative with any number of pixels,

so long as they are arranged symmetrically in the surface of the element through which the light passes, such that a pixel with alignment in one direction always has a corresponding pixel with orthogonal alignment to compensate it. It is further understood that all of the above-mentioned embodiments for making the attenuator polarization independent are only examples of arrangements whereby this is achieved. Any suitable embodiment, wherein the phase shift of the light through the phase shifting element or elements is arranged to be identical for two orthogonal directions of polarization, is also suitable for ensuring polarization independent operation of the variable attenuators of the present invention.

It is appreciated by persons skilled in the art that the present invention is not limited by what has been particularly shown and described hereinabove. Rather the scope of the present invention includes both combinations and subcombinations of various features described hereinabove as well as variations and modifications thereto which would occur to a person of skill in the art upon reading the above description and which are not in the prior art.

CLAIMS

We claim:

1. A variable optical attenuator comprising:

an input fiber for receiving an input optical signal to be attenuated;

an output fiber for outputting said attenuated optical signal;

at least one phase changing element, disposed in the optical path between said input fiber and said output fiber; and

a drive source operative to change the phase of light passing through at least part of said at least one element.

2. A variable optical attenuator according to claim 1 and wherein said change in the phase of light passing through said at least part of said at least one element is operative to change the mode structure of at least part of said input optical signal such that said part of said input optical signal cannot propagate freely in said output fiber.

3. A variable optical attenuator according to claim 2, and wherein said input optical signal has an effectively fundamental mode structure and said output fiber is a single mode fiber, and wherein said mode structure of at least part of said input optical signal is changed to a higher order mode, such that said part of said input signal cannot propagate freely through said output fiber.

4. A variable optical attenuator according to any of claims 1 to 3, and wherein said at least one phase changing element is a liquid crystal element.

5. A variable optical attenuator according to claim 4, and wherein said at least one phase changing element comprises a serial pair of parallel aligned liquid crystals, orthogonally aligned such that said attenuator is insensitive to the

direction of polarization of said optical signal.

6. A variable optical attenuator according to claim 4, and wherein said at least one phase changing element comprises a serial pair of 90° twist liquid crystals, aligned in parallel such that said attenuator is insensitive to the direction of polarization of said optical signal.

7. A variable optical attenuator according to claim 4, and wherein said at least one phase changing element comprises a liquid crystal divided into at least two orthogonally aligned pixels, such that said attenuator is insensitive to the direction of polarization of said optical signal.

8. A variable optical attenuator according to any of claims 1 to 3, and wherein said phase changing element is selected from a group consisting of an electro-optic element, a Faraday effect element and a magneto-optical element.

9. A variable optical attenuator according to any of claims 1 to 8, and wherein said part of said element is defined by at least one pixel on said element.

10. A variable optical attenuator according to claim 9, and wherein said at least one pixel is two pixels.

11. A variable optical attenuator according to claim 9, and wherein said at least one pixel is four pixels, and said drive source is operative to change the phase of light passing through two diagonally opposite ones of said pixels

12. A variable optical attenuator according to any of claims 1 to 11, and wherein said input fiber and said output fiber are disposed such that light passes by transmission between them.

13. A variable optical attenuator according to any of claims 1 to 11, and also comprising a reflecting surface, and wherein said input fiber and said output fiber are disposed such that light passes by reflection between them.

14. A variable optical attenuator according to claim 13, and wherein said reflecting surface is formed on the rear side of said phase changing element.

15. A variable optical attenuator according to any of claims 9 to 14, and wherein said at least one pixel is formed by means of at least one pixelated electrode located essentially over said at least one pixel.

16. A variable optical attenuator according to any of claims 9 to 14, and wherein said at least one pixel is formed by means of at least one electrode located remotely from said at least one pixel.

17. An optical attenuator comprising an input fiber, an output fiber and at least one phase changing element operative to change the phase of part of the cross section of light passing from said input fiber to said output fiber.

18. An optical attenuator according to claim 17, and wherein said change in the phase of part of the cross section of light passing from said input fiber to said output fiber is such that the mode structure of said light is changed such that said light cannot propagate freely in said output fiber.

19. An optical attenuator according to claim 18, and wherein said input fiber is a single mode fiber, and said output fiber is a single mode fiber, and wherein said mode structure of at least part of said light is changed to a higher order mode, such that said part of said light cannot propagate freely in said output fiber.

20. An optical attenuator according to any of claims 17 to 19, and wherein

said at least one phase changing element is a liquid crystal element.

21. An optical attenuator according to claim 20, and wherein said at least one phase changing element comprises a serial pair of parallel aligned liquid crystals, orthogonally aligned such that said attenuator is insensitive to the direction of polarization of said light.

22. An optical attenuator according to claim 20, and wherein said at least one phase changing element comprises a serial pair of 90° twist liquid crystals, aligned in parallel such that said attenuator is insensitive to the direction of polarization of said light.

23. An optical attenuator according to claim 20, and wherein said at least one phase changing element comprises a liquid crystal divided into at least two orthogonally aligned pixels, such that said attenuator is insensitive to the direction of polarization of said light.

24. An optical attenuator according to any of claims 17 to 23, and wherein said at least one phase changing element is pixelated.

25. An optical attenuator according to any of claims 17 to 24, and wherein said change in the phase of part of the cross section of light is effected by means of electrodes associated with said at least one phase changing element.

26. An optical attenuator according to claim 25, and wherein said attenuator is a variable attenuator.

27. An optical attenuator according to any of claims 17 to 26, and wherein said input fiber and said output fiber are disposed such that light passes by transmission between them.

28. An optical attenuator according to any of claims 17 to 26, and also comprising a reflecting surface, and wherein said input fiber and said output fiber are disposed such that light passes by reflection between them.

29. An integrated phase changing element for use in a variable optical attenuator, comprising a pixelated phase changing element, at least one detector element, and drive circuitry for controlling the phase change introduced in the passage of light through at least one of the pixels of said pixelated phase changing element.

30. A multichannel gain equalizer comprising:

an input fiber;

a demultiplexer having an array of output channels, connected to said input fiber;

an output fiber;

a multiplexer having a plurality of input channels, connected to said output fiber;

a plurality of variable optical attenuators, each attenuator of said plurality being connected between an output channel of said demultiplexer and an input channel of said multiplexer; and

a plurality of signal detectors, each signal detector of said plurality being operative to adjust the attenuation of one of said attenuators according to the level of said signal detected; and

wherein at least one of said variable optical attenuators comprises a phase changing unit operative to change the phase of part of the cross section of light passing through it.

31. A multichannel gain equalizer according to claim 30, and wherein each of said signal detectors is connected in series with one of said attenuators.

32. A multichannel gain equalizer according to claim 30, and wherein each of said signal detectors is located remotely from said gain equalizer.

33. A multichannel gain equalizer according to claim 30, and wherein said demultiplexer comprises a concave dispersive grating.

34. A multichannel gain equalizer according to claim 30, and wherein said multiplexer comprises a concave dispersive grating.

35. Apparatus according to any of the preceding claims and substantially as shown and described hereinabove.

36. Apparatus according to any of the preceding claims and substantially as shown and described in any of the drawings.

For the applicant:

Sanford T. Colb
Advocates and Patent Attorneys
C: 40771

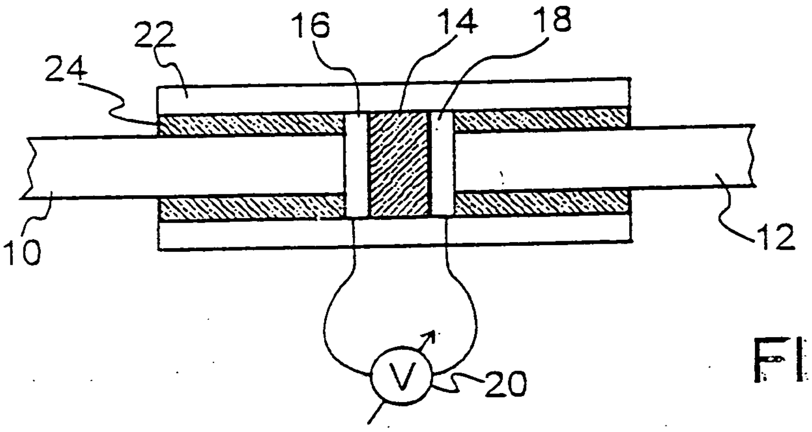


FIG. 1

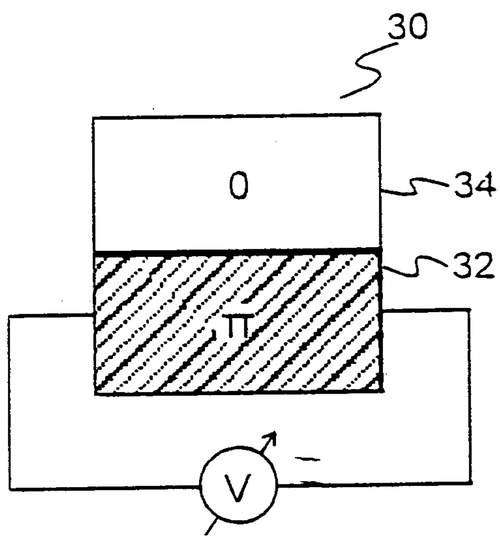


FIG. 2

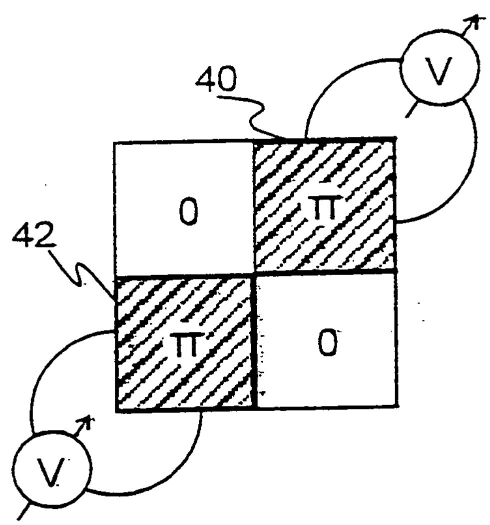


FIG. 3

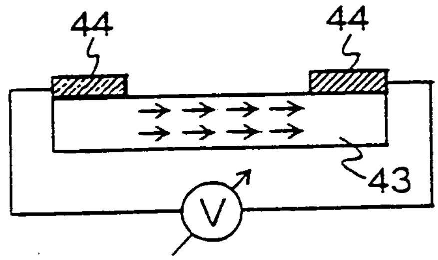


FIG. 4

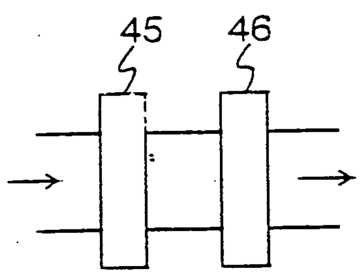


FIG. 5A

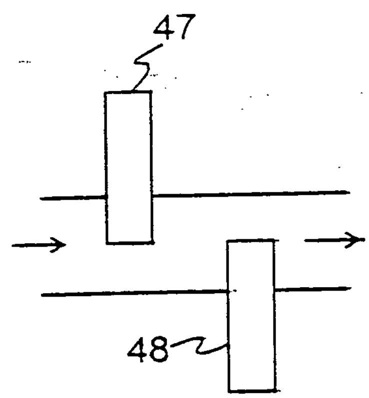


FIG. 5B

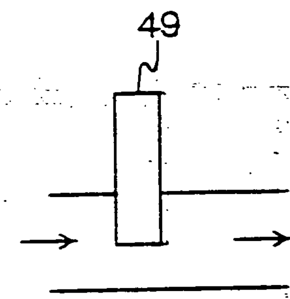


FIG. 5C

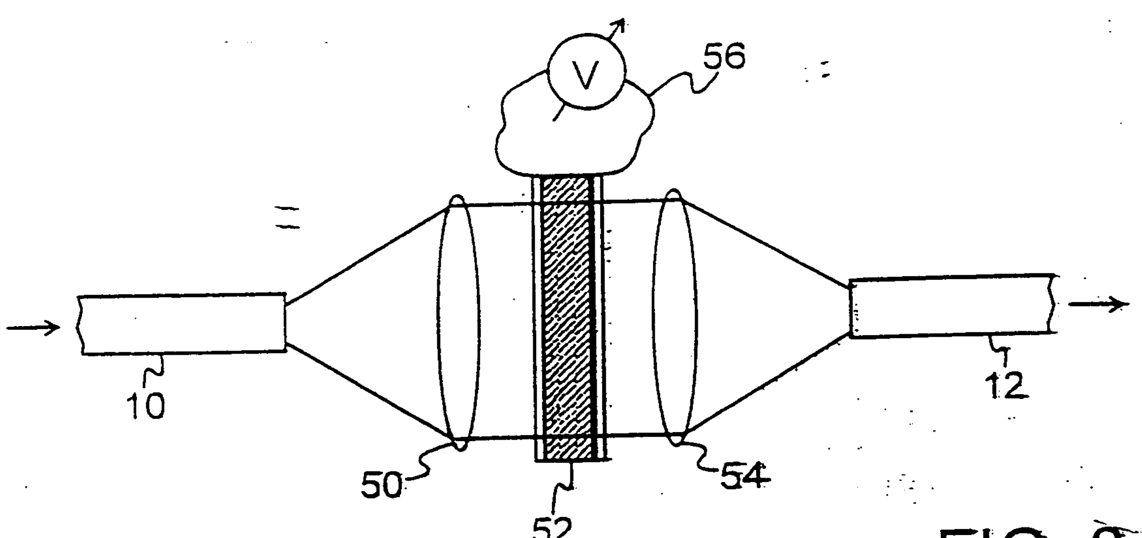


FIG. 6

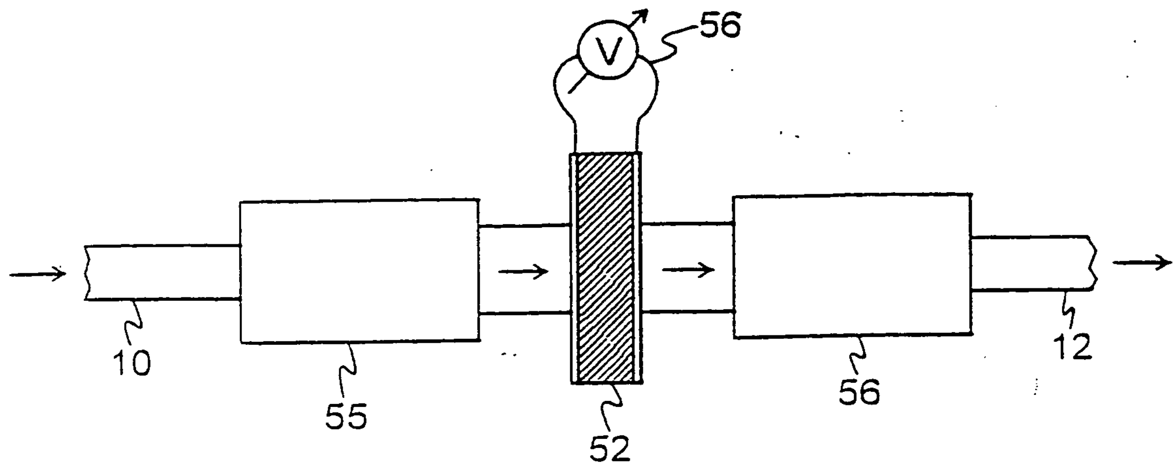
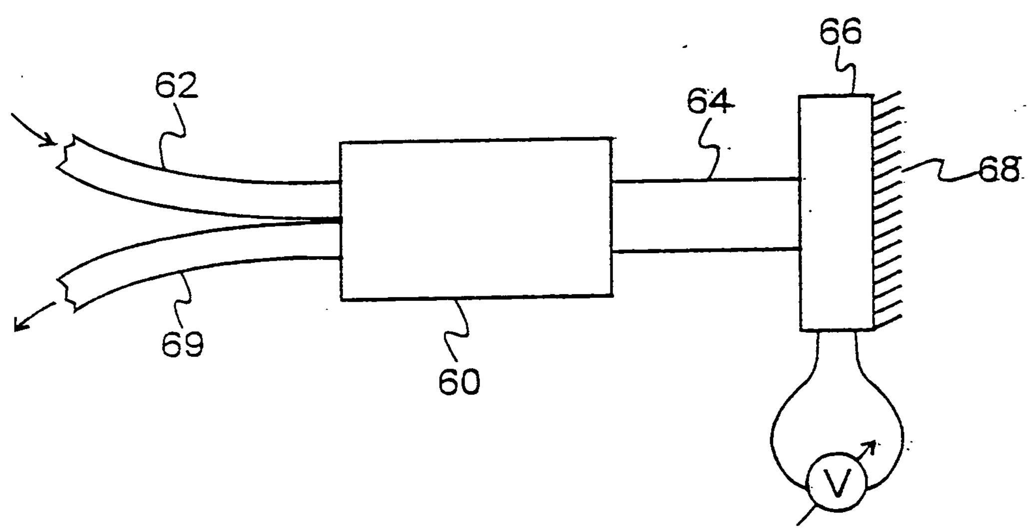


FIG. 7

FIG. 8



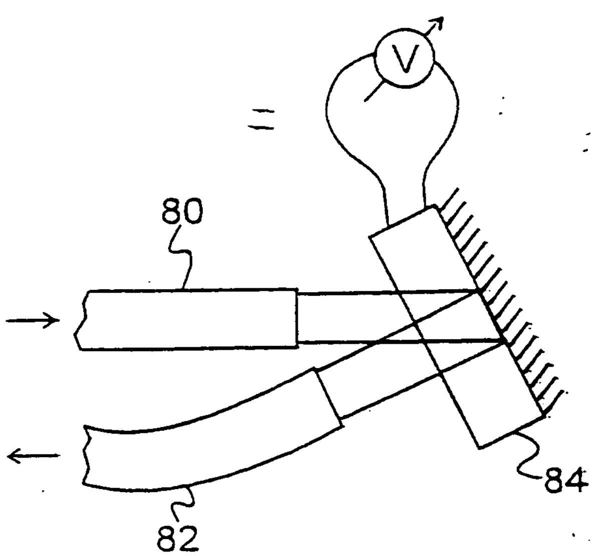


FIG. 9

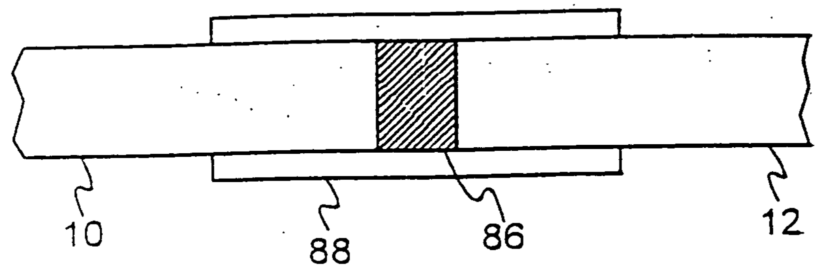


FIG. 10

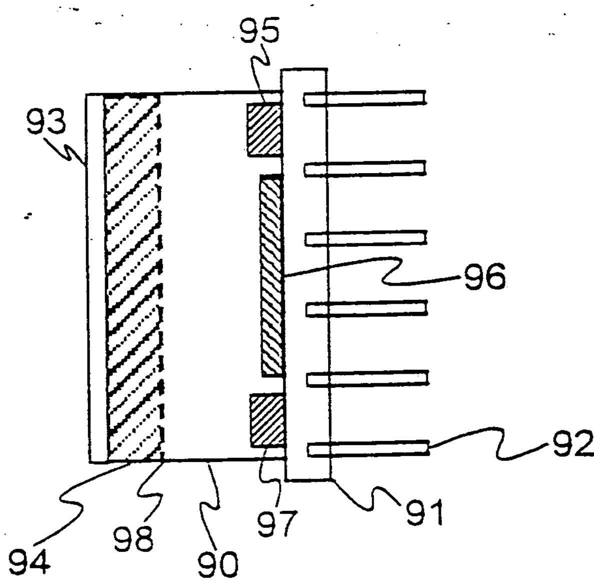


FIG. 11A

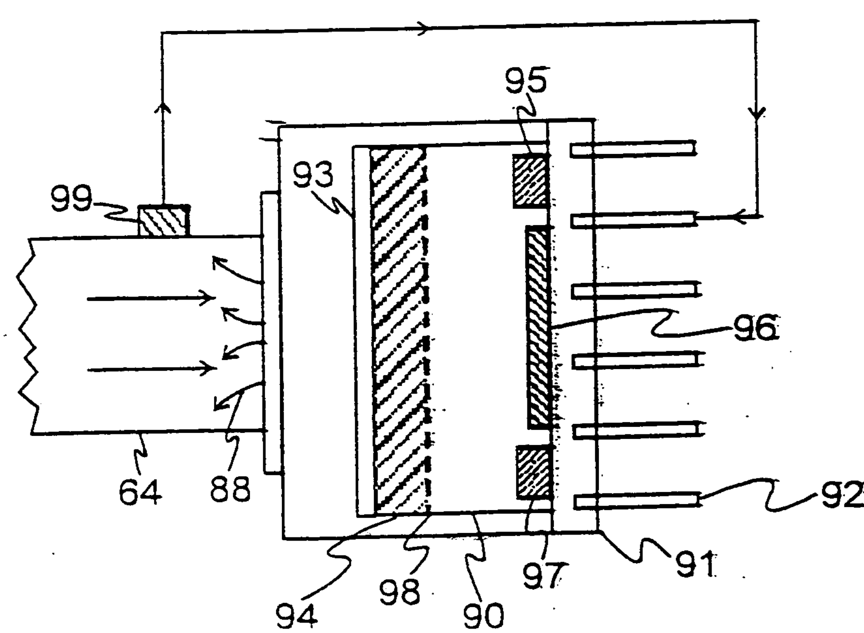


FIG. 11B

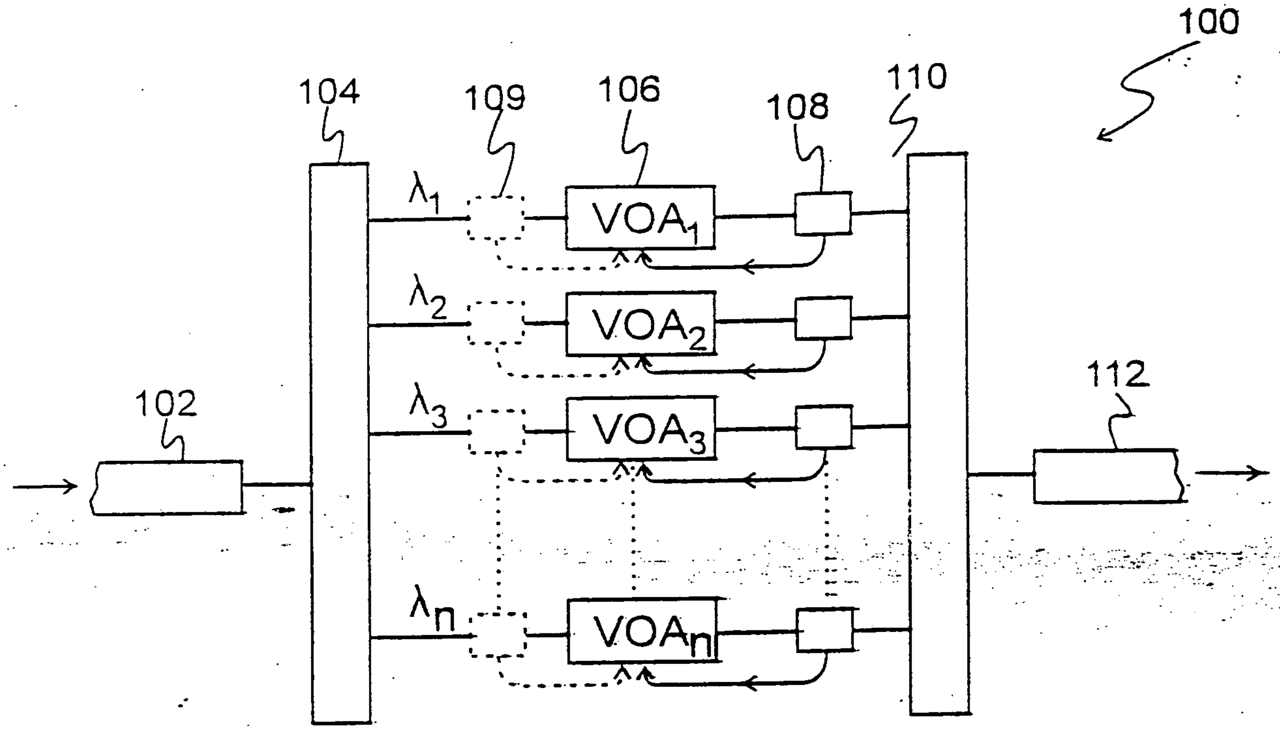

100
104
109
106
108
110
λ_1
VOA$_1$
λ_2
VOA$_2$
λ_3
VOA$_3$
102
112
λ_n
VOA$_n$

FIG. 12

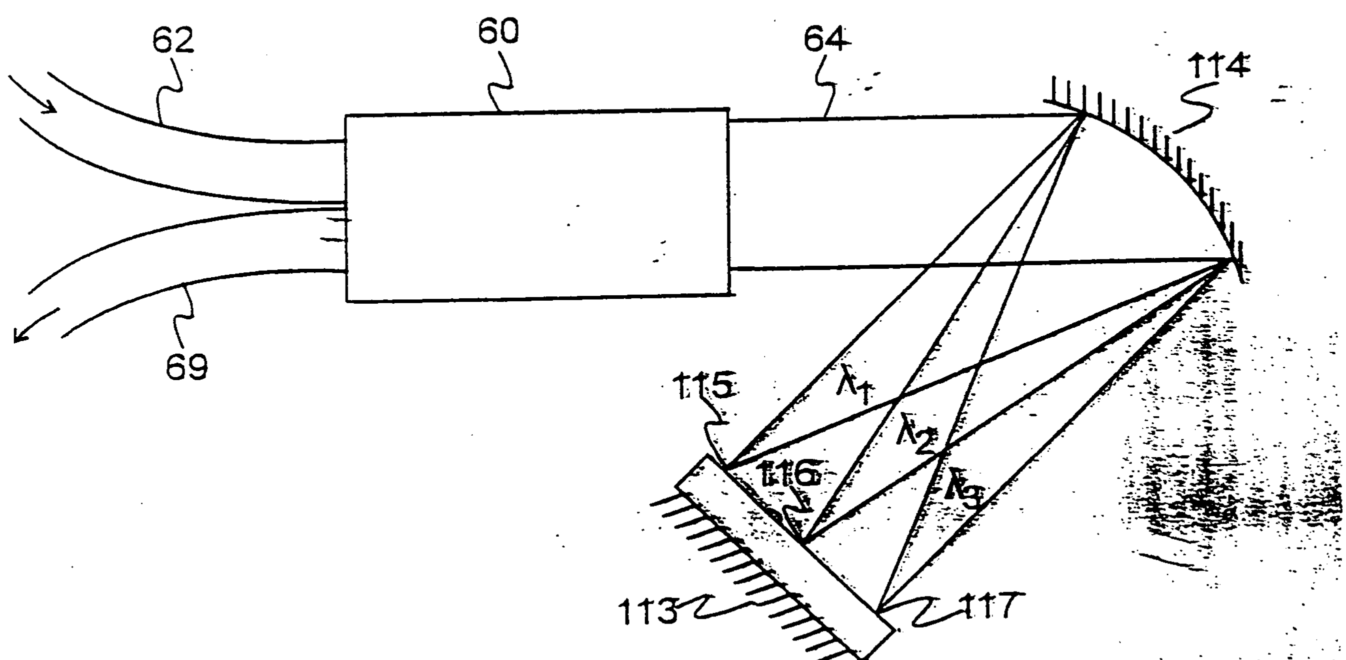

62
60
64
114
69
115
λ_1
λ_2
116
λ_3
113
117

FIG. 13

FIG. 14A

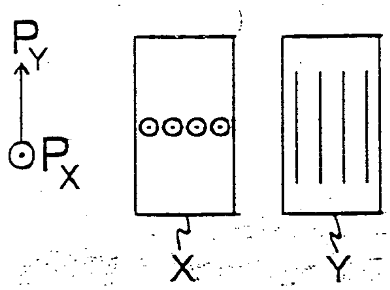


FIG. 14B

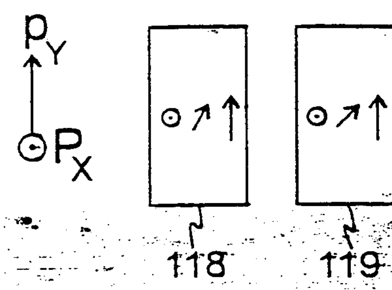
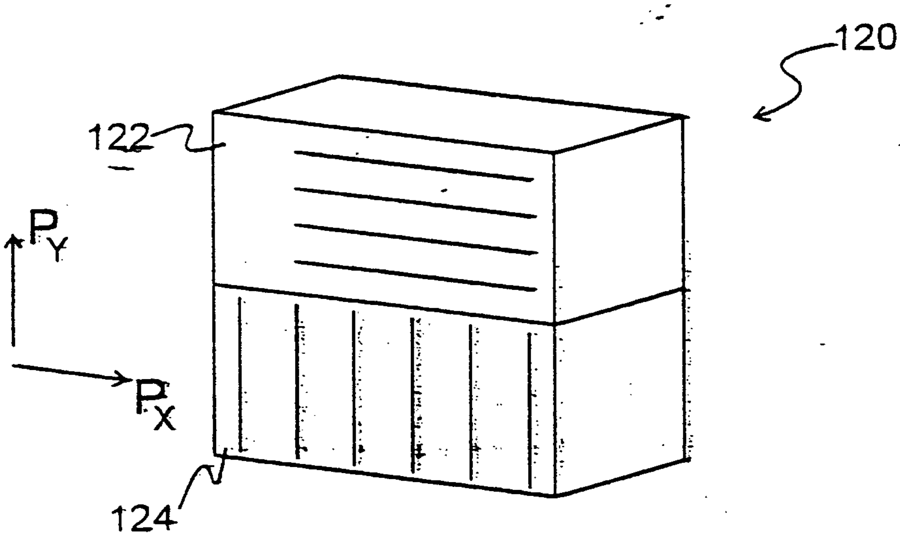


FIG. 14C



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